J/ψ azimuthal anisotropy relative to the reaction plane in Pb-Pb collisions at 158 GeV per nucleon

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Abstract

The J/ψ azimuthal distribution relative to the reaction plane has been measured by the NA50 experiment in Pb-Pb collisions at 158 GeV/nucleon. Various physical mechanisms related to charmonium dissociation in the medium created in the heavy ion collision are expected to introduce an anisotropy in the azimuthal distribution of the observed J/ψ mesons at SPS energies. Hence, the measurement of J/ψ elliptic anisotropy, quantified by the Fourier coefficient v_2 of the J/ψ azimuthal distribution relative to the reaction plane, is an important tool to constrain theoretical models aimed at explaining the anomalous J/ψ suppression observed in Pb-Pb collisions. We present the measured J/ψ yields in different bins of azimuthal angle relative to the reaction plane, as well as the resulting values of the Fourier coefficient v_2 as a function of the collision centrality and of the J/ψ transverse momentum. The reaction plane has been estimated from the azimuthal distribution of the neutral transverse energy detected in an electromagnetic calorimeter. The analysis has been performed on a data sample of about 100 000 events, distributed in five centrality or p_T sub-samples. The extracted v_2 values are significantly larger than zero for non-central collisions and are seen to increase with p_T.

1 Introduction

Charmonium production and suppression is one of the most powerful probes for a phase transition to deconfined matter in heavy-ion collisions at the energies of the CERN SPS. In particular, the J/ψ suppression in proton-nucleus and nucleus-nucleus reactions has been intensively studied in the last 2 decades by the NA38 and NA50 experiments. The J/ψ suppression observed in proton-nucleus reactions is understood as due to absorption of charmonium states on ordinary nuclear matter with $\sigma_{abs} = 4.2 \pm 0.5$ mb [1]. The J/ψ/Drell-Yan ratio measured in S-U and peripheral Pb-Pb collisions results to be in agreement with the expectation from ordinary nuclear absorption as measured in p-A reactions, while an anomalous extra suppression is present in semi-central and central Pb-Pb collisions [2].

Additional insight into charmonium suppression mechanisms can be obtained from the anisotropy of the overlap region of the projectile and target nuclei in collisions with impact parameter b> 0 [3, 4, 5]. The initial geometrical anisotropy gives rise to an observable anisotropy in particle distributions if the created system is interacting strongly enough to thermalize at an early stage and develop collective motion (flow). Hence, anisotropic transverse flow should be observed for J/ψ's formed by c-$\bar{c}$ recombination if the charm quarks have undergone strong enough rescatterings leading them to thermalize in the first stages of the system evolution. J/ψ flow is however not expected to be established at SPS energies where early charm thermalization is unlikely and $c\bar{c}$ recombination is negligible. Nevertheless, other mechanisms related to $c\bar{c}$ absorption in the medium created in the collision, essentially $c\bar{c}$ dissociation by the hard gluons present in the deconfined phase [4, 5] and by co-moving hadrons [3] are predicted as possible sources of J/ψ anisotropy already at SPS energies.

The azimuthal anisotropy is usually quantified from the coefficients of the Fourier series describing the particle azimuthal distribution:

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})] \tag{1}$$

where Ψ_{RP} is the reaction plane angle defined by the impact parameter vector in the transverse plane. An azimuthal dependent J/ψ absorption pattern determined by the anisotropic geometrical shape of the nuclear overlap region is expected to give rise to a measurable second harmonic coefficient v_2, which describes an elliptic anisotropy. It is anticipated [4, 5] that elliptic anisotropy due to J/ψ dissociation by gluons resulting from the formation of a deconfined medium should vanish for peripheral collisions (where the critical temperature is not attained) and for central collisions (because of the isotropic geometry of the overlap region), showing a sudden onset in correspondence of the phase transition and a maximum for semi-central collisions ($E_{\rm T}\approx$70-80 GeV in [4] or $N_{\rm part}\approx$200-220 in [5]).

2 Experimental setup, data selection and reaction plane estimation

The NA50 apparatus consists of a muon spectrometer equipped with three detectors to measure centrality-related observables on an event-by-event basis and specific devices for beam tagging and interaction vertex identification. A detailed description of the detectors can be found in [6]. Minimal details are given here for specific detectors relevant for the present analysis.

Anisotropy studies have been done on the sample of about 100,000 J/ψ's collected by experiment NA50 in year 2000 with the SPS Pb beam at 158 GeV/nucleon (see [2]). The J/ψ is detected via its $\mu^+\mu^-$ decay in the pseudo-rapidity range $2.7 \leq \eta_{\rm lab} \leq 3.9$. The analysis is performed in the dimuon kinematic domain $0 < y_{\rm cm} < 1$ and $-0.5 < \cos(\theta_{\rm CS}) < 0.5$, where $y_{\rm cm}$ is the rapidity in the center-of-mass system and $\theta_{\rm CS}$ is the polar decay angle of the muons in the Collins-Soper reference frame.

The study of the centrality dependence of the J/ψ anisotropy is based on 5 bins of the neutral transverse energy ($E_{\rm T}$) as measured by an electromagnetic calorimeter (see fig. 1). This calorimeter is made up of lead and scintillating fibers and it measures event-by-event the transverse energy carried by neutral particles produced in the interaction (mostly due to $\pi^0 \to \gamma\gamma$ and to direct γ) in the pseudo-rapidity window $1.1 \leq \eta_{\rm lab} \leq 2.3$. The $E_{\rm T}$ limits for the 5 bins are reported in table 1 together with the average values of impact parameter and number of participants estimated by means of a Glauber calculation including the resolution of the calorimeter.

The reaction plane is estimated making use of the azimuthal segmentation in six azimuthal sectors (sextants) of the electromagnetic calorimeter, as represented in fig 1 where it can also be seen that each sextant is further subdivided into four

Bin	$\mathrm{E_{T,min}}$ (GeV)	$\mathrm{E_{T,max}}$ (GeV)	$\langle \mathrm{b} \rangle$ (fm)	$\langle \mathrm{N_{part}} \rangle$
1	10	30	10.5	64
2	30	50	8.3	134
3	50	70	6.5	203
4	70	90	4.8	271
5	90	120	2.7	342

Table 1: E_{T} limits, average values of impact parameter and number of participants for the centrality bins used in this analysis.

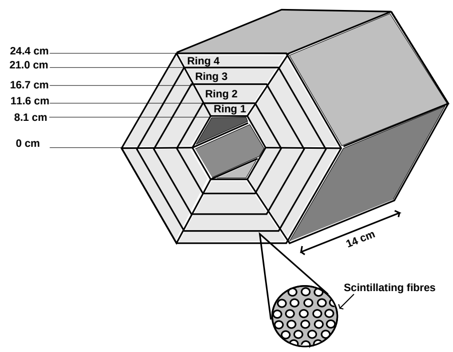


Figure 1: Geometrical segmentation of the electromagnetic calorimeter.

radial rings, each of them covering a different pseudo-rapidity range. The event plane angle Ψ_n (estimator of the unknown reaction plane angle Ψ_{RP}) is given by:

$$\Psi_n = \frac{1}{n}\tan^{-1}\left[\frac{\sum_{i=1}^{6} \; w^i \; E_{\mathrm{T}}^i \; \sin(n\Phi_i)}{\sum_{i=1}^{6} \; w^i \; E_{\mathrm{T}}^i \; \cos(n\Phi_i)}\right] \tag{2}$$

where n is the considered Fourier harmonic, E_{T}^i the neutral transverse energy measured in sextant i, and Φ_i the azimuthal angle defined by the center of sextant i (see fig. 1). The weighting coefficients w^i are introduced to make the event plane distribution isotropic and are defined as $< E_{\mathrm{T}}^{tot} > /(6 < E_{\mathrm{T}}^i >)$. Their values range between 0.994 and 1.012, resulting in a very small event-plane flattening correction. The event plane Ψ_2 has been used to calculate the elliptic anisotropy [1]. It is computed from the π° azimuthal distribution in the backward rapidity region, where, at SPS energies, pions show positive v_2 [8, 9, 10] and therefore it is directed in-plane (i.e. parallel to the reaction plane).

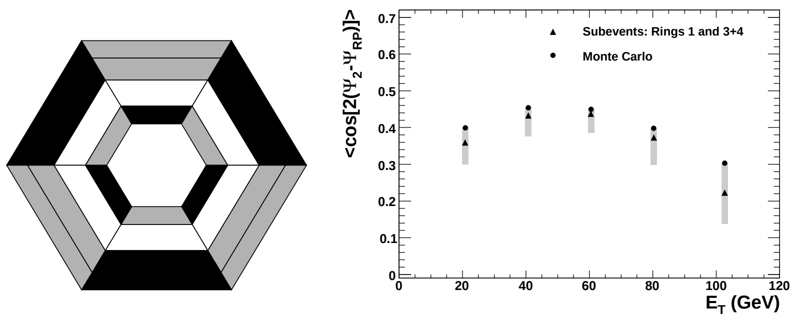
The event plane resolution (expressed as $< \cos\left[2\left(\Psi_2 - \Psi_{RP}\right)\right] >$) has been estimated in two independent ways. The results are shown in fig. 2b. The first technique is based on Monte Carlo simulations of the detector response taking as input the value of v_2 measured by the calorimeter [10]. The sextant to sextant fluctuations are tuned to reproduce the experimentally observed distribution of the quantity:

$$b_3 = \frac{\sum_{k=1}^{6} \sin\left[3(2k-1)\frac{\pi}{6}\right] E_{Tk}}{\pi \mathrm{sinc}\frac{3\pi}{6}} \tag{3}$$

with sinc $x = (\sin x)/x$. For symmetry reasons, b_3 is sensitive only to statistical fluctuations and not to azimuthal anisotropies [10]. The gray band represents the

[1]The event plane Ψ_1 could also be used, but the resolution is worse [7].

systematic error coming from the systematic uncertainty on v_2 due to the presence of non-flow correlations. The second technique makes use of the ring segmentation of the calorimeter to define two sub-events. The resolution is extracted from the angular correlation between the event plane angles of the two sub-events. A scheme of the sub-event definition is shown in fig. 2a: ring 2 has been removed from the analysis in order to have a rapidity gap limiting non-flow correlations between the two sub-events, while the alternate pattern of rings and sextants is dictated by the need of having the two sub-events equally populated. The energy collected by the excluded ring 2 is then accounted for when using the formulas from [7] to extrapolate the measured resolution of the sub-event plane to the resolution of the event plane of the full calorimeter. As it can be seen in fig. 2b the resolutions extracted with the two methods agree within the systematic uncertainties, so the Monte Carlo estimation together with its systematic error bar is used to calculate the J/ψ elliptic anisotropy.



(a) (b)

Figure 2: (a) Sketch of the geometrical configuration used for sub-event definition. (b) Second harmonic event plane resolution with from Monte Carlo simulations and sub-events technique.

3 Analysis and results

The J/ψ azimuthal distribution relative to the reaction plane is extracted using two different analysis schemes. The first one extracts the number of J/ψ's in different intervals of azimuthal angle relative to the event plane. The second one computes the Fourier coefficient v_2 from the J/ψ azimuthal distribution. For each analysis, specific methods are implemented in order to separate the J/ψ signal from the other dimuon sources under the J/ψ mass peak[2].

3.1 Number of J/ψ's in bins of azimuthal angle

Two different analysis methods have been developed to extract the number of J/ψ's in two wide bins of azimuthal angle relative to the event plane ($\Delta\Phi_2 = \Phi_{dimu} - \Psi_2$ where Φ_{dimu} is the dimuon azimuthal angle and Ψ_2 the second harmonic event plane from eq. 2).

The first method consists in fitting the mass spectra of opposite-sign dimuon sub-samples in bins of centrality (E_{T}) and dimuon azimuthal angle relative to the measured event plane ($\Delta\Phi_2$). The mass spectra above 2.5 GeV/c^2 (see fig. 3-left) are fitted to the four signal contributions (namely J/ψ, ψ', Drell-Yan and open charm) with shapes determined from detailed Monte Carlo simulations of the NA50 apparatus. The combinatorial background is evaluated from the like sign pairs (see [2] for

[2]About 90% of the reconstructed opposite-sign dimuons in the mass range $2.9 < M < 3.3$ GeV/c^2 and in the kinematic domain defined above originate from J/ψ decays.

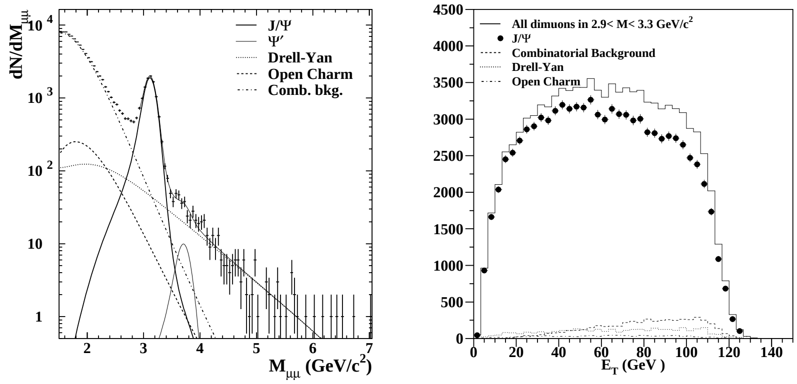


Figure 3: Left: Example of fit to the $\mu^+\mu^-$ mass spectrum. Right: E_{T} spectra (not corrected for centrality-dependent inefficiencies) of $\mu^+\mu^-$ in $2.9 < M < 3.3$ GeV/c^2.

details). This analysis method is limited by the low statistics of high-mass Drell-Yan dimuons which are crucial to fix the Drell-Yan contribution in the fitting procedure. Hence, it is not possible to divide the full sample of dimuon events in more than 10 bins (5 centrality $\times$ 2 $\Delta\Phi_2$ intervals)

The second method consists in building, for each $\Delta\Phi_2$ bin, the E_{T} spectrum of all the $\mu^+\mu^-$ in the mass range $2.9 < M < 3.3$ GeV/c^2 and then subtracting the spectra of the different sources of background. The E_{T} spectra of the various dimuon contributions in $2.9 < M < 3.3$ GeV/c^2 are shown in fig. 3-right. The combinatorial background is extracted from like-sign muon pairs. The DY spectrum is estimated from $\mu^+\mu^-$ in the mass range 4.2<M<7.0 GeV/c^2 and rescaled, via Monte Carlo simulations, to $2.9 < M < 3.3$ GeV/c^2. The $D\bar{D}$ yield is estimated from opposite sign dimuons in 2.1<M<2.7 GeV/c^2 after combinatorial background and DY subtraction and rescaled to the J/ψ mass range. The dimuons from ψ' decay in $2.9 < M < 3.3$ GeV/c^2 are negligible. The underlying assumption is that the E_{T} spectra of the involved physical processes do not depend on the invariant mass range used for their determination within the range under study. This "counting" method allows for a larger number of E_{T} bins, thus providing a better insight on the centrality dependence of the possible anisotropy. It should be noted that no correction for centrality-dependent inefficiencies is applied to the E_{T} spectra because in the following analyses only relative numbers of J/ψ's in different $\Delta\Phi_2$ bins are considered.

The presence of an azimuthal dependent J/ψ absorption is expected to result in a different number of particles emitted parallel (in-plane) and orthogonal (out-of-plane) to the reaction plane as a consequence of the geometrical shape of the overlap region of the colliding nuclei. The elliptic anisotropy is therefore quantified starting from the numbers N_{IN} and N_{OUT} of J/ψ's observed in two cones with an opening angle of 90° centered respectively at $\Delta\Phi_2$=0° (in-plane) and at 90° (out-of-plane), see fig. 4. So:

$$N_{IN} = \int_{-\pi/4}^{\pi/4} \frac{dN}{d(\Delta\Phi_2)} d(\Delta\Phi_2) + \int_{3\pi/4}^{5\pi/4} \frac{dN}{d(\Delta\Phi_2)} d(\Delta\Phi_2) \tag{4}$$

$$N_{OUT} = \int_{\pi/4}^{3\pi/4} \frac{dN}{d(\Delta\Phi_2)} d(\Delta\Phi_2) + \int_{5\pi/4}^{7\pi/4} \frac{dN}{d(\Delta\Phi_2)} d(\Delta\Phi_2) \tag{5}$$

The anisotropy is then quantified as the ratio $(N_{IN} - N_{OUT})/(N_{IN} + N_{OUT})$. A positive anisotropy comes from a larger number of J/ψ's observed in plane than out-of-plane. If only a second (elliptic) harmonic is present, i.e. $dN/d\Phi_{dimu} \propto$

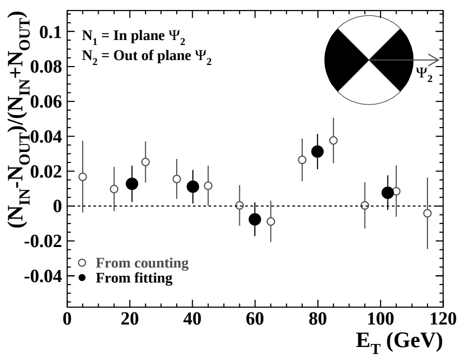


Figure 4: Anisotropy vs. E_{T} as extracted from the number of J/ψ's in $\Delta\varphi_n$ bins centered in-plane and out-of-plane (right). Error bars represent statistical errors on the measured points.

$1 + 2v_2 \cos[2(\Phi_{dimu} - \Psi_{RP})]$, then:

$$\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}} = \frac{4}{\pi} v_2 \qquad (6)$$

It should be noted that the resolution of the event plane has not been taken into account in the calculation of the anisotropy from N_{IN} and N_{OUT} and therefore the comparison with the values of the Fourier coefficient v_2 reported in the next section is not straightforward. The results for the elliptic anisotropy as a function of E_{T} are shown in fig. 4. The two analyses agree in indicating on average a small excess of J/ψ's emitted in-plane (positive anisotropy). The largest signal is observed in the centrality bin 70<E_{T}< 90 GeV.

3.2 Fourier coefficient v_2 of J/ψ's

The second coefficient of the Fourier expansion is given by: $v_2 =< \cos[2(\Phi_{dimu} - \Psi_{RP})] >$ where the average is performed over events in a given centrality (or p_{T}) bin. Since the reaction plane (Ψ_{RP}) is unknown, the event plane (calculated from neutral transverse energy anisotropy) has to be used instead, obtaining $v_2' =< \cos[2(\Phi_{dimu} - \Psi_2)] >$. The quantity v_2' should then be corrected for the event plane resolution [7], obtaining $v_2 = v_2' / < \cos[2(\Psi_2 - \Psi_{RP})] >$.

Two different analysis methods have been used to subtract the background and extract the values of J/ψ elliptic anisotropy v_2. The first estimation is obtained from the average of the $\cos[2(\Phi_{dimu} - \Psi_2)]$ distributions of $\mu^+\mu^-$ in the mass range $2.9 < M < 3.3$ GeV/c^2 after subtracting the background contributions with the same "counting" procedure described above. The $\cos[2(\Phi_{dimu} - \Psi_2)]$ distribution of combinatorial background is estimated from like-sign muon pairs, while the ones of DY and $D\bar{D}$ are extracted from different $\mu^+\mu^-$ mass intervals and rescaled to the J/ψ mass range under the assumption that they do not depend on the invariant mass range considered.

A second evaluation of v_2 in the 5 E_{T} bins has been obtained from the number of J/ψ's extracted with the "counting" method in 8 bins of azimuthal angle relative to the event plane. The coefficient v_2' is obtained by fitting the resulting number of J/ψ's in bins of $\Delta\Phi_2$ with the function

$$N^{J/\psi}(\Delta\Phi_2) = K\left[1 + 2 \cdot v_2' \cos(2\Delta\Phi_2)\right] \qquad (7)$$

where $\Delta\Phi_2 = \Phi_{dimu} - \Psi_2$ and the free parameters of the fit are K and v_2'. Afterward, v_2 is obtained by applying to v_2' the correction factor for the event plane resolution.

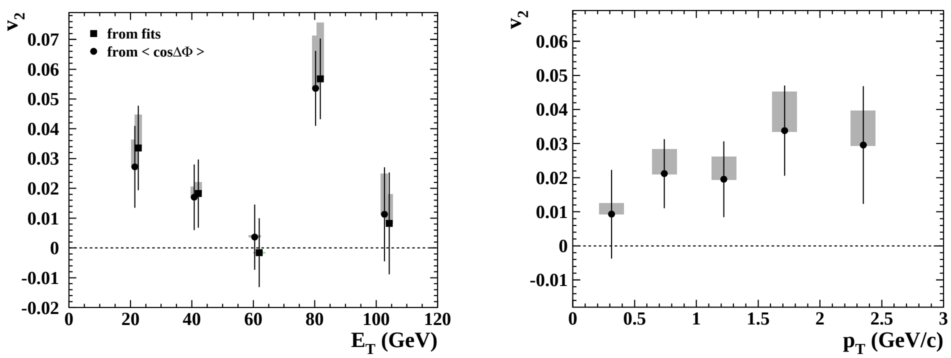


Figure 5: Fourier coefficient v_2 vs. $E_{\rm T}$ (left) and J/ψ $p_{\rm T}$(right). Error bars represent statistical errors, the gray band is the systematic error coming from the estimation of the event plane resolution.

The results for v_2 vs. $E_{\rm T}$ are shown in fig. 5-left. The two analysis methods are in remarkable agreement and show positive values of v_2, confirming the excess of J/ψ's exiting in-plane. A maximum v_2 is observed for the bin $70<E_{\rm T}<90$ GeV, corresponding to $N_{part} \approx 270$ and $\langle$b$\rangle$=4.8 fm. The error bars represent the statistical error on the measurement of the J/ψ anisotropy, while the gray bands are the systematic errors coming from the uncertainty on the estimation of the event plane resolution. The analysis based on the $\cos[2(\Phi_{dimu} - \Psi_2)]$ spectra has been applied also in bins of J/ψ transverse momentum. The obtained results for v_2 as a function of $p_{\rm T}$ (centrality integrated) are shown in 5-right. The J/ψ v_2 shows an increasing trend with increasing $p_{\rm T}$.

4 Conclusions

J/ψ elliptic anisotropy relative to the reaction plane has been measured by NA50 from a data sample of 100000 J/ψ's produced in Pb-Pb collisions at 158 GeV/nucleon ($\sqrt{s}$ = 17.2 GeV). The anisotropy has been quantified both from the normalized difference between the number of J/ψ's emitted in plane and out-of-plane and from the Fourier coefficient (v_2) which describes an elliptic anisotropy. These quantities have been measured as a function of collision centrality (defined by the neutral transverse energy $E_{\rm T}$ produced in the collision) and as a function of J/ψ transverse momentum. A positive v_2 is measured: more J/ψ's are observed in-plane than out-of-plane. The largest anisotropy is observed in the centrality bin with $N_{part} \approx 270$ and $\langle$b$\rangle$=4.8 fm. The elliptic anisotropy is observed to increase with increasing J/ψ $p_{\rm T}$.

References

[1] B. Alessandro et al. (NA50 Collaboration), Eur. Phys. Journ. **C48** (2006) 329.

[2] B. Alessandro et al. (NA50 Collaboration), Eur. Phys. Journ. **C39** (2005) 335.

[3] H. Heiselberg and R. Mattiello, Phys. Rev. **C60** (1999) 044902.

[4] X. N. Wang and F. Yuan, Phys. Lett. **B540** (2002) 62.

[5] X. Zhu, P. Zhuang and N. Xu, Phys. Lett. **B607** (2005) 107.

[6] M.C. Abreu et al. (NA50 Collaboration), Phys. Lett. **B410** (1997) 327.

[7] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. **C58** (1998) 1671.

[8] C. Alt at al (NA49 collaboration), Phys. Rev. **C68** (2003) 034903.

[9] M.M. Aggarwal et al. (WA98 collaboration), Nucl. Phys. **A762** (2005) 129.

[10] M. C. Abreu et al. (NA50 Collaboration), Nucl. Phys. Proc. Suppl. **92** (2001) 55.